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Acoustic wave sensors: design, sensing mechanisms and applications

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Abstract. Acoustic waves are currently being used in a wide range of sensor fields including physical sensing, chemical sensing and biosensing. Their implementation requires specific knowledge of materials, acoustic wave properties, device design and the sensing mechanisms involved for a wide range of applications. In this paper, the authors report on commonly used acoustic wave devices in sensor applications as well as the design techniques and fabrication processes. Sensing mechanisms and a portable sensor array system are described. The development of IC-based processes, thin-film deposition and sensitive layer fixation will allow for the integration of a total physical and chemical analysis system in the one IC package, leading to the evolution of smart sensors.

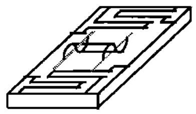
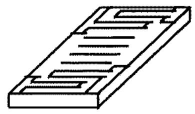
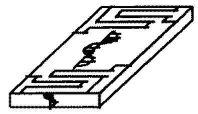
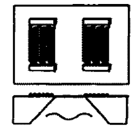
1. Introduction

Acoustic wave (AW) devices have received increasing interest in recent years in a wide range of applications where they are currently used as resonators, filters, sensors and actuators. The AW family of devices includes the surface acoustic wave (SAW), the shear horizontal surface acoustic wave (SH SAW), the shear horizontal acoustic plate mode (SH APM), the flexural plate wave (FPW) or Lamb wave mode and thickness shear mode (TSM) devices. Although AW devices are already fabricated on a large scale for telecommunication systems such as the case in the mobile telephone industry, their development in the sensors field is still in the early stages. AW devices are highly sensitive to surface perturbation and changes. Thus, they are investigated as sensors for measurement in both gas and liquid environments. Measurement of parameters such as temperature, pressure, liquid density, liquid viscosity, electrical conductivity, mass and visco-elastic changes of thin films have been reported in a number of reviews [1–6].

AW-based sensors can be sensitive to a combination of parameters at the same time. To avoid sensitivity overlaps, different kinds of acoustic device have been used as well as adjustment of material properties, e.g. anisotropy and piezoelectricity. Piezoelectricity is the main possibility investigated to conveniently generate acoustic waves. Bulk materials are the most commonly used but piezoelectric thin films such as ZnO and AlN have emerged as viable alternatives. Others possibilities such as magnetostrictive or electrostrictive materials can be used to generate acoustic waves. Development of thin-film processes and micromachining technologies will greatly contribute to the development of AW-based sensors. The potential of Si material for micro-electro-mechanical systems (MEMS) is evident with the possibility of combining mechanical and electrical properties. Furthermore, the generation of acoustic waves in Si-based microstructures will open the door to the development of smart sensors [7]. They may include an array of sensors with different waves or different sensitive layers together with pumps, motors, actuators and signal processing electronics. This is one of the promising possibilities for Si material and the driving force for future developments of AW sensors. Since it requires various processes and technologies, compatibility is one of the main limitations. At the same time, bulk piezoelectric materials have been well characterized with detailed investigations into the technologies, and, subsequently, they have been used to elucidate various sensing mechanisms. Portable sensor arrays are being developed. Versatile AW sensors are implemented as well as electronic circuitry for auto-calibration, enhancement of selective sensitivity and reproducibility.

In this paper the authors report on commonly used AW devices in sensor applications. The design, sensing mechanisms and instrumentation associated with these

Table 1. AW devices and comparison of their operation.

	Rayleigh SAW	SH SAW	SH APM	Lamb wave FPW
Substrate	ST-quartz	Lithium tantalate	Lithium niobate ST-quartz	Si_xN_y/ZnO
f_0 (MHz)	160	110	160	1–6
				
U [a]	transverse parallel	transverse	transverse	transverse parallel
U_t [b]	normal	parallel	parallel	normal
Medium	gas	gas liquid	gas liquid	gas liquid

[a] Particle displacement relative to the wave propagation direction.
[b] Transverse component relative to the sensitive surface.

sensors are presented. Finally, some examples from our studies are used to illustrate this paper.

2. Acoustic waves and devices

Traditional gravimetric-based sensors include those based on acoustic devices such as the SAW, the SH SAW, the SH APM and FPW, or Lamb wave. Different AW propagation is characterized by each device in terms of the substrate material and the particle displacements relative to the direction of wave propagation and to the sensitive surface. These devices can operate in either a gas or liquid medium, depending upon their physical properties. The sensing mechanism is generally a function of parameter perturbation affecting the propagating AW on the surface of the sensor. A comparison of the principles of operation for the various AW sensors is illustrated in table 1 [1].

3. Design techniques and fabrication

3.1. Design techniques

The design procedure for acoustic sensors is mainly device and application specific. Issues such as acoustic mode selection and sensitivity, substrate selection, transducer geometry and the selective (bio)chemical film deposition technique all need to be considered when investigating acoustic sensor designs. The final operational environment is also an important influence in the design procedure: consideration of gas/liquid delivery systems need to be made, especially for integrated flow chambers.

SAW devices utilize interdigital transducers (IDTs) that are fabricated onto a substrate to generate Rayleigh waves. The Rayleigh mode SAW has predominantly two particle displacement components in the sagittal plane. Surface particles move in elliptical paths with a surface normal and a surface parallel component. The surface parallel component is parallel to the direction of propagation (table 1). The electromagnetic field associated with the acoustic wave travels in the same direction. The wave velocity is determined by the substrate material and the cut of the crystal. The energies of the SAW are confined to a zone close to the surface a few wavelengths thick [8]. A SAW delay line consists of two IDTs on the surface of a piezoelectric substrate, one to launch the SAW and the other to detect it. The use of Rayleigh SAW sensors is applicable only to gas media as the Rayleigh wave is severely attenuated in liquid media [9].

SH SAW devices are very similar to the SAW devices, but the selection of a different crystal cut yields shear horizontal surface waves instead of the Rayleigh waves. The particle displacements of this wave are transverse to the wave propagation direction and parallel to the plane of the surface (table 1), hence the suitability for SH SAW devices to operate in liquid media, where propagation at the solid/liquid interface can be achieved with minimal energy losses [10]. The appearance of these devices is similar to that of Rayleigh SAW devices, but a thin solid film or grating is added to prevent wave diffraction into the bulk. The frequency of operation is determined by the IDT finger spacing and the wave velocity for the particular substrate material. An example piezoelectric substrate is lithium tantalate ($LiTaO_3$), where the dominant acoustic wave propagating on 36°-rotated Y-cut, X propagating $LiTaO_3$ is an SH mode. The AW propagation is not severely attenuated when the surface is loaded with a liquid, as is the case with the Rayleigh SAW-based devices [11–13].

Acoustic plate mode devices can be divided into two main categories according to the vibration plate polarization: SH APM devices where the propagation is transverse and Lamb wave devices where the plate can vibrate as symmetrical and antisymmetrical modes (flexural modes). These modes can be generated in thin piezoelectric plates and their frequencies are determined by both the material properties and by the thickness to wavelength ratio. Fabrication of APM devices requires additional design procedures for the fabrication of the thin plates with respect to the IDT periodicity. For this we can use bulk piezoelectric materials, either quartz [14, 15] or $LiNbO_3$ sliced into thin plates [16]. Most of the SH APM devices are based on this design because of the ability to choose the appropriate crystallographic orientation allowing for the generation of shear waves. According to the restrictions of manual handling and the fabrication process, the minimum thickness is limited to around 100 μm (microns).

Generally, Lamb modes require thinner plates. For this the etching process is another alternative for the fabrication of thin membranes. This development has been achieved by means of micromachining technology based on IC processes, piezoelectric thin-film deposition and silicon etching [7].

Examples of reported design techniques that have been developed are those for SAWs [17, 18], SH SAWs [12, 19], SH APMs [14, 15] and Lamb waves [7, 20]. The common design theme is the optimization of the acoustic transducer and associated electronic interface, for both discrete and integrated implementations. For the design of acoustic-based oscillator configurations, for example, electrical parameter matching between the acoustic device and the driving amplifier is essential in order to realize a stable, low-noise oscillating system [21]. The instability of this oscillating frequency should be kept well below the minimum frequency response to a sensing interaction.

3.2. Acoustic wave transducer fabrication

Acoustic wave devices are fabricated using processes that have been primarily developed for IC technology in the microelectronics industry. The adoption of silicon fabrication creates the possibility for the integration of the acoustic devices and electronic driving circuitry, leading to the development of smart sensors [7]. Compatibility of the technologies is the biggest challenge facing the development of these smart sensors. While total integration of the different processes is limited, the adoption of process modules seems promising [20]. The technique involves the localization of specific fabrication steps to common areas so as to minimize the total number of process steps in the fabrication process, thus aiming to maintain device integrity and quality. Both SAW and Lamb wave devices are compatible for the silicon implementation [20, 22–24], whereas the majority of reported SH APM and SH SAW mode devices have been fabricated using standard bulk piezoelectric substrates [12, 13, 16, 25–27]. To the best of our knowledge, there has been no previous work reporting generation of SH SAWs or SH APMs with piezoelectric thin films deposited by sputtering and so on. Their polarization seems to be not appropriate for shear vibration generation mainly because of the C-axis being near the normal of the surface.

The general structure of both the Si integration and bulk piezoelectric acoustic devices (including SAWs, SH SAWs and SH APMs) is shown in figure 1. For the Si integration structure, a piezoelectric ZnO layer performs the coupling of the acoustic waves. Other thin films, such as AlN, have been reported due to its temperature coefficient and its electromechanical coupling [24]. The SiO2 thin layer acts as an adequate electric insulating layer as well as providing a suitable substrate for the growth of high-quality ZnO films [22]. For the standard bulk piezoelectric acoustic devices, materials that offer a compromise between a high electromechanical coupling and low temperature coefficient are preferred. Processes that modify the bulk piezoelectric substrates, especially in the region of acoustic propagation, for the improvement of the substrate properties are gaining more interest. One such promising technique is the proton exchange of lithium niobate and lithium tantalate substrates, where a ferroelectric inversion layer is created, affecting the substrate properties [28, 29].

A summary of the AW sensor fabrication process is shown in figure 2. The type of acoustic device and the selection of the substrate determines which process module is implemented. To realize the interdigital structures on the surface of the acoustic device for either the Si integration substrate or the bulk piezoelectric substrate, commonly used planar fabrication processes such as the *etching* and *lift-off* methods are used. The *etching* procedure involves the selective etching away of unwanted metal patterns after a development step which removes either exposed or unexposed photoresist from the surface of the substrate. A positive mask is used in the photolithography step and the subsequent removal of unwanted metal is dependent upon the type of photoresist used, whether positive or negative. The *lift-off* procedure utilizes a negative mask in the photolithography step to develop patterned photoresist structures with a characteristic 'lip' prior to the deposition of a metal layer. This facilitates a discontinuity at the patterned structure edges when a metal is evaporated on the surface of the wafer; thus the removal of unwanted metal is subsequently easily achieved.

4. Sensing mechanisms and instrumentation

Since AW devices use piezoelectric materials for the excitation and the detection of the acoustic waves, the nature of almost all of the parameters involved with sensor applications concerns either mechanical or electrical perturbations. An acoustic device is thus sensitive mainly to physical parameters which may interact with (perturb) mechanical properties of the wave and/or its associated electrical field. For chemical sensors or biosensors some transduction layers should be used to convert the value of the desired parameter (chemical agent concentration, etc) into a mechanical or electrical perturbation that can disturb the AW properties. In general, the acoustic phase velocity can be affected by many factors, each of which possesses a potential sensor response. Equation (1) illustrates the perturbation of the acoustic velocity by the mass (*mass*), electrical (*elec*), mechanical (*mech*) and environmental (*envir*) parameter properties.

$$\frac{\Delta V}{V_{acoustic}} \cong \frac{1}{V_{acoustic}} \left(\frac{\partial V}{\partial mass} \Delta mass + \frac{\partial V}{\partial elec} \Delta elec + \frac{\partial V}{\partial mech} \Delta mech + \frac{\partial V}{\partial envir} \Delta envir \right). \tag{1}$$

A sensor response may be due to a combination of these parameters, hence the problem of overlapping sensitivities needs to be addressed. The use of sensor arrays and integrated sensor systems for the development of total analysis systems is therefore essential for gaining a better understanding of the sensing mechanisms.

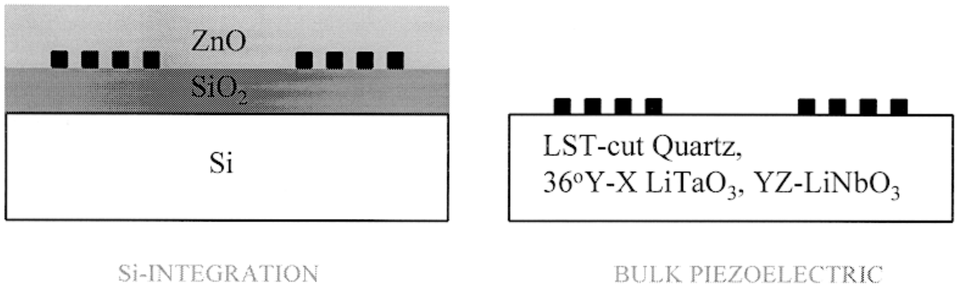


Figure 1. The structure of Si integration and bulk piezoelectric acoustic devices.

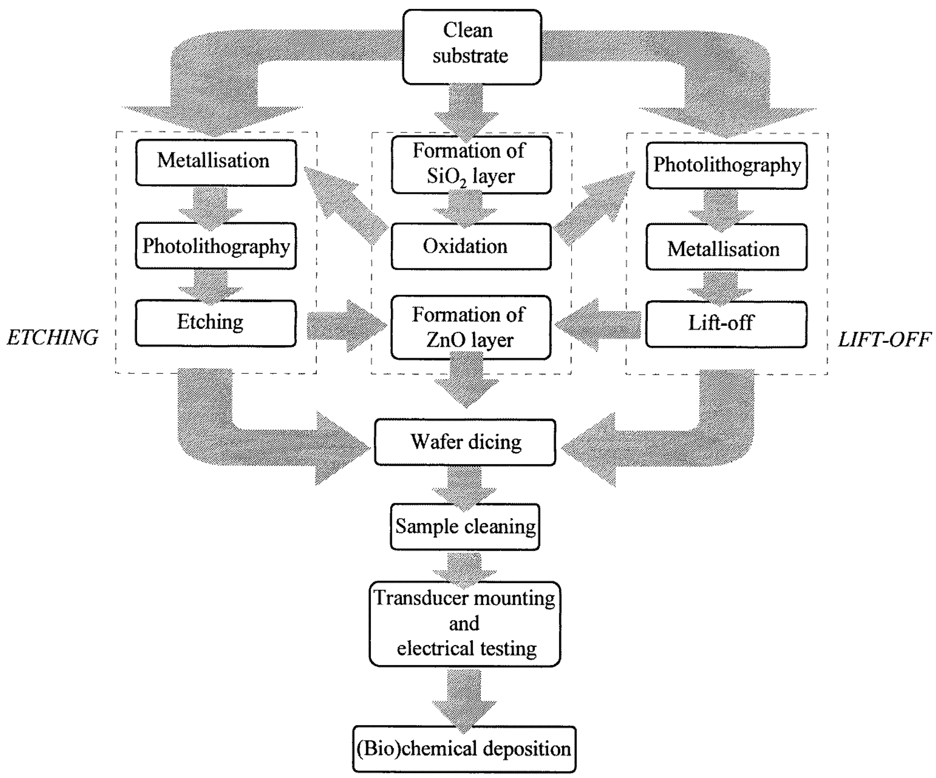


Figure 2. An overview of the AW sensor fabrication process.

In the following section, the authors briefly describe examples of some potential parameters that can be sensed with an AW device. Examples of some interesting applications are also presented.

4.1. Parameter sensitivity

4.1.1. Temperature. The effect of temperature is one of the easiest parameters that can be sensed because almost all physical and chemical effects depend on temperature. In certain applications, the effect of temperature should be minimized in order to avoid any interference with other effects. For acoustic wave sensors, the temperature effect induces dimensional dilatations and small changes in the mechanical and electrical properties. Two kinds of interaction can thus be measured: (i) shift of the AW velocity due to intrinsic changes of material properties (elasticity, density, etc) (this is the case for almost all SAW devices using thick materials [30]) and (ii) for acoustic devices for which the resonant frequency or the velocity is dependent on the dimensional values (SH APM, Lamb wave devices, thickness shear mode, ...), temperature can affect changes of both material properties and boundary conditions [31].

Until now quartz has been used for thermal compensation possibilities but other mechanisms can be exploited to use other materials:

(i) proton exchange of lithium niobate and lithium tantalate substrates, where a ferroelectric inversion layer is created, affecting the substrate properties [28, 29];

(ii) for layered structures, use of materials with opposite thermal coefficients [24].

An interesting application of the influence of temperature on SAW sensor response is the measurement of gas

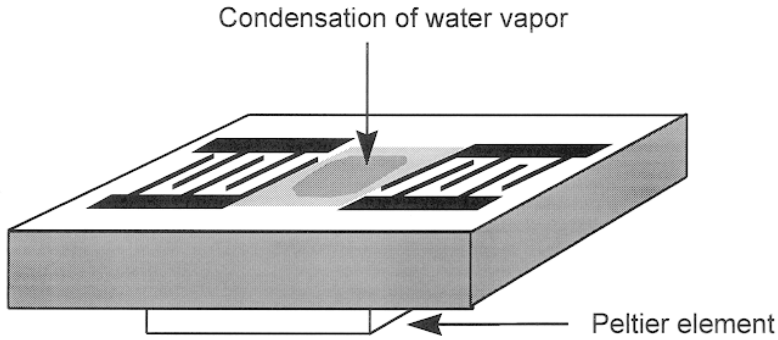


Figure 3. The principle of a SAW dew-point sensor.

flow rate. A SAW delay line fabricated on 128°-rotated Y-cut $LiNbO_3$ was heated above ambient temperature by either a patterned substrate heater [32] or by use of an acoustic absorber that converts the RF energy to heat via acoustic dissipation [33]. The flow of the gas over the SAW devices causes heat to be carried away by convection. This lowers the temperature of the substrate, thus perturbing the acoustic velocity which is related to a change in frequency of the oscillator circuit. A frequency change greater than 142 kHz for a flow rate variation from 0 to 1000 $cm^3\ min^{-1}$ was reported.

An example from the present authors' research is the application of a SAW dew-point humidity sensor [34]. Based on a hygrometric technique, the surface of a SAW device is cooled by a Peltier element until water vapour condensation occurs (figure 3).

When water vapour condensation appears on the Rayleigh wave propagation path, it induces a substantial attenuation of the wave amplitude and a measurable shift in the associated oscillator's frequency due to mass loading (figure 4). In order to elucidate the influence of temperature and the dew deposition, a thermocouple was deposited on the wave propagation path. This allows us to exploit the frequency–temperature dependence with an LST quartz-cut substrate which has a linear frequency–temperature response. The frequency varies with a linear slope before the condensation, but, when the dew appears, the slope increases rapidly due to the mass loading effect. The dew-point temperature is then directly obtained via the coordinates of the intersection point.

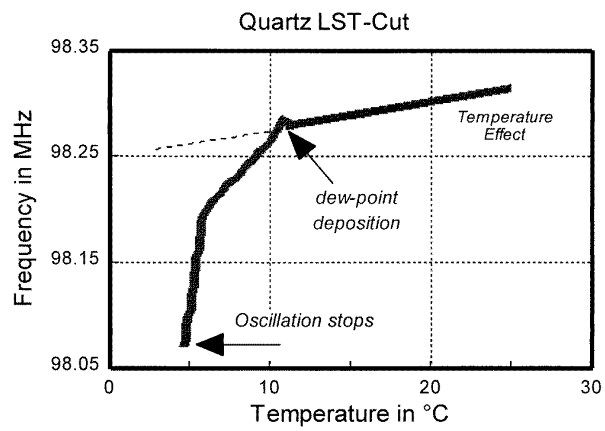


Figure 4. The effect of dew deposition on the frequency–temperature curve.

4.1.2. Pressure. Acoustic devices are sensitive to mechanical loading, such as pressure. The first reported application of SAW technology for a sensing function, for example, was for a SAW pressure sensor [35]. The acoustic wave is affected by the strain induced by an associated pressure and, when implemented in a SAW oscillator configuration, this strain may be interpreted via a shift in the resonant frequency of the SAW device. More recent advances in Lamb wave technology has lead to the development of novel pressure sensor structures [36]. They reported the micromachining fabrication of an AlN/silicon structure and a pressure sensitivity of 2.7 ppm $mbar^{-1}$ was achieved. The use of opposite temperature coefficients of the two materials allowed for the realization of a self-compensating structure, with a temperature sensitivity of 0.9 ppm $^\circ C^{-1}$.

The effect of pressure as an interferant in a sensing application needs also to be addressed and compensated. The use of a parallel reference sensor is the most popular method for compensation and can be implemented via the use of an array of acoustic sensors.

4.1.3. Mass loading. One of the most interesting sensing mechanisms of acoustic sensor response is mass loading. Applications are found in areas such as film thickness monitoring, gas and liquid media chemical sensing and biosensing. Specifically, (bio)chemical sensors based on acoustic devices offer a unique and very attractive means to sense species in either a gas or liquid media. They provide excellent sensitivity, ruggedness, direct frequency output and good stability. The devices can perform a (bio)chemical sensing function by the application of some (bio)chemical coating to the substrate of the device that selectively reacts with the desired entity to be sensed. This interaction produces a measurable shift in the resonant frequency of the device. Different sensing applications can be achieved by changing the selective (bio)chemical coating.

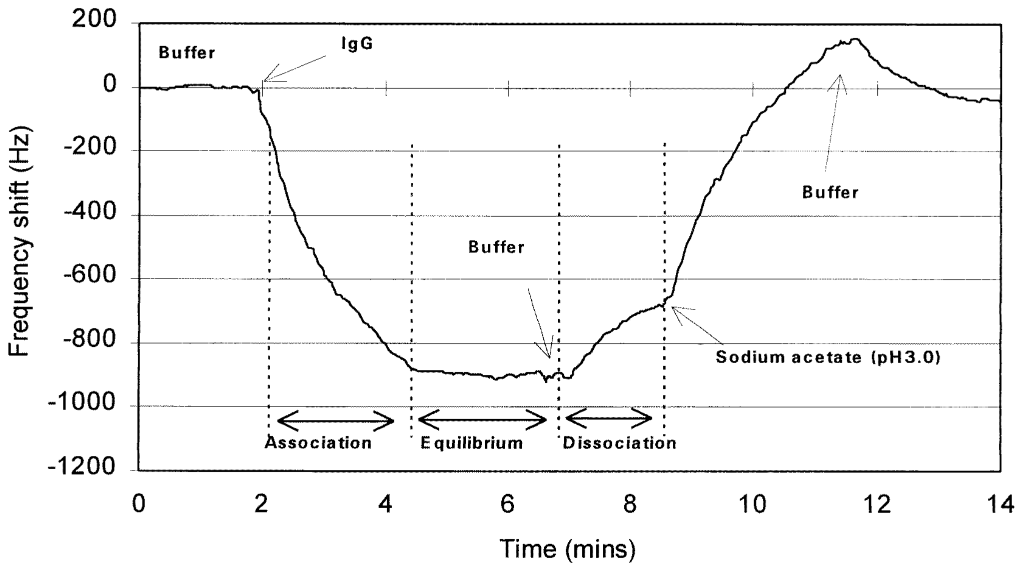


Figure 5. The frequency response of the protein A immobilized 52 MHz SH SAW sensor to IgG (100 ng ml^{-1}). Kinetic phases of the immuno-interaction are shown (flow rate 0.8 ml min^{-1}, temperature 25 ± 0.1 °C).

The mass sensitivities of the different acoustic devices are related to the structure geometry and resonant center frequency [1]. In general, the mass sensitivity for SAW and SH SAW devices increases with increasing center frequency. For SH APM devices mass sensitivity increases on increasing the center frequency (decreasing the plate thickness) for a constant wavelength. For Lamb wave devices mass sensitivity increases on decreasing the center frequency (decreasing the plate thickness) for a constant wavelength.

The acoustic sensor response to mass loading requires careful interpretation to identify the sensing mechanism. The problem of overlapping sensitivities to a number of parameters (such as temperature, pressure and viscosity) may inhibit the understanding of the process. AW-based gas sensors and biosensors are especially prone to this problem and much research has been focused towards the development of arrays and smart sensor systems to address this.

The present authors have developed a novel SH SAW-based immunosensor system for the continuous and direct detection of biological interactions [19]. An array of SH SAW sensors was implemented using the portable acoustic array system. The interaction between bovine immunoglobulin G (IgG) and protein A was investigated to establish the validity of the proposed sensing system. The sensing interaction predominantly causes a perturbation in the sensor response as a function of mass and mechanical loading. The influence of viscosity must also be considered for both the sample fluids and from the result of the immuno-interaction. Analysis of the kinetic phases of the interaction were evaluated in real time and preliminary results clearly showed that a fast, highly sensitive and reproducible response is obtainable for various IgG concentrations in the range of 10^{-7}–10^{-1} mg ml^{-1}. Figure 5 shows a typical SH SAW kinetic response to IgG (100 ng ml^{-1}) at a constant flow rate (0.8 ml min^{-1}). Fast regeneration of the protein A immobilized surface was achieved with an acid wash.

4.1.4. Viscoelasticity. The investigation of the viscosity of fluids is vital for mechanical, chemical and biochemical systems and processes. In the area of biosensors, for example, a biochemical interaction may be accompanied by a variation in the viscoelasticity of the interface. This may interfere with the desired sensing parameter under investigation, hence careful investigation of the influence of viscosity is required for all sensing applications in liquid media. Both SH APM and SH SAW devices are most suited for the application of viscosity sensing due to their high sensitivity and their acoustic waves being polarized predominantly in the plane of the sensing surface. This results in only viscous coupling to the liquid affecting the properties of the AW, which can be related to fluid viscosity [11, 14, 15]. The surface components of the waves are coupled viscously to the adjacent liquid, causing motion of the liquid in a thin layer adjacent to the sensor surface [14]. Hoummady and Bastien reported that the liquid relaxation time becomes increasingly significant for increasing viscosities which limits the dynamic viscosity sensing range to about 600 cP [15]. They found that operation at higher frequencies (170–230 MHz) with respect to the liquid relaxation times allows for the investigation of the effect of elasticity. The experimental device is shown in figure 6.

Pulsed operation measurements were performed. From a comparison of the amplitude of echoes with and without a liquid on the quartz, calibration was obtained by reference to the viscosity of different water–glycerin mixtures at a given temperature. Figure 7 shows the associated loss for one reflection at the quartz/liquid interface for various glycerin–water mixtures. Both the viscous (slope region) and elastic (level region) modes of the liquid are evident.

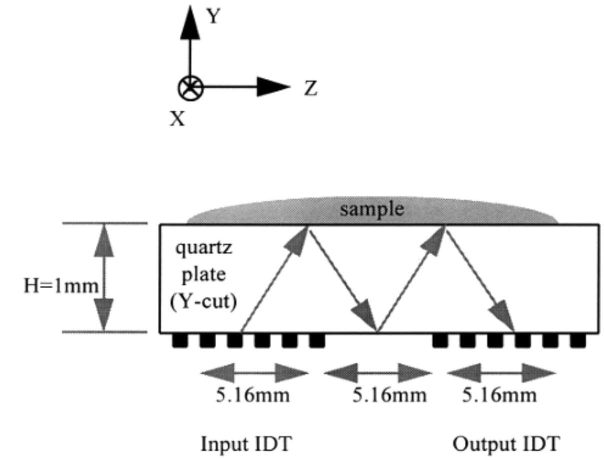


Figure 6. The SH APM device for viscosity measurements.

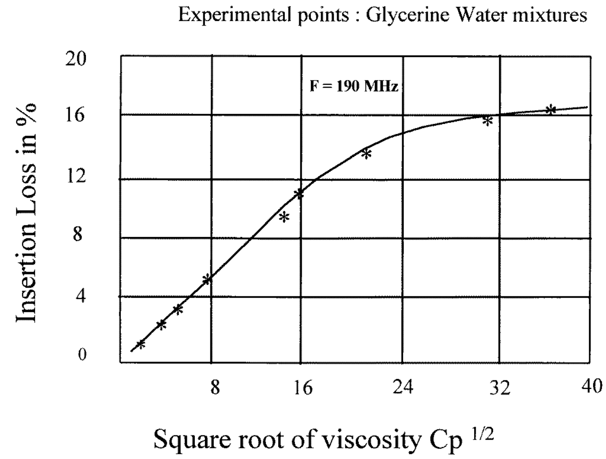


Figure 7. The insertion loss (%) of the SH APM device for various viscosities. ∗, experimental points; ——, theoretical curve.

4.1.5. Conductivity. Conductivity is another important parameter that has direct influence on the response of acoustic sensors for both gas and liquid medium applications. The sensing mechanism is related to the acoustoelectric effect where the electrical boundary conditions for the propagating acoustic wave are perturbed by some conductive thin film or conductive liquid. For a conductive thin film deposited on a SAW device, for example, the quasistatic field associated with the acoustic wave interacts with the charge carriers in the film [37]. The effect of liquid conductivity has also been reported for both SH APM [16] and SH SAW [12, 13] sensors. The common theme of the conductive type of acoustic sensor is that the sensing mechanism allows for rapid sensor responses, thus enabling for the fast, real time analysis of the sensing interaction.

A novel SAW-based ozone sensor application was proposed by Banda *et al* [17, 18]. The sensing principle is based on conductivity changes of an ozone selective film during the interaction with ozone gas. When a SAW propagates on a piezoelectric substrate ($LiNbO_3$) coated with the selective film (200 Å thick film of In_2O_3), the quasi-static electric field associated with the SAW interacts with the charge carriers of the film. The SAW velocity is therefore dependent on the film conductivity changes. These velocity changes can easily be interpreted as a shift in the resonant frequency, when the SAW delay line is incorporated in an oscillator configuration. The SAW sensor was heated up to 200 °C, for which an oscillation frequency of the system of 162.94 MHz was attained. Figure 8 shows the frequency response versus time of the sensor when exposed to alternate concentrations of ozone of 50 and 150 ppb. The maximum relative change of frequency for the device for an ozone concentration of 150 ppb was 300 ppm (∼49 kHz for 162.9 MHz center frequency). Calibration of the $LiNbO_3$ SAW ozone sensor was performed for the range 0–150 ppb.

The present authors have investigated the acoustoelectric interaction between an SH SAW sensor and different commercial brands of natural still spring water [12]. The sensing mechanism is based upon perturbation of the electrical properties of the adjacent liquid. The SH SAW sensors were implemented in an oscillator configuration and interfaced to the portable acoustic wave array system. Figure 9 shows the transient response (frequency and attenuation) analysis of an Evian™ sample. Both the change in frequency and the attenuation of the sensor response are interpreted as characteristic features of each individual water sample.

Pattern recognition techniques were then applied for the discrimination between four different brands of sample liquids. The neural network technique used was based upon the back-propagation algorithm, with the input layer being a pre-processed representation of the SH SAW sensor responses and the output layer indicating the sample liquid classification. Discrimination between the four types of sample liquid was achieved with an overall recognition probability of 90% across a large sample size.

4.2. An acoustic wave sensor array system

The need for chemical sensor arrays for the investigation of chemical species has long been recognized where the problems of sensor selectivity, sensitivity and reversibility are addressed. Subsequently, novel AW sensor array systems for both liquid and gas media have been developed by the present authors [12, 19, 38]. The focus of the research has been towards the development of portable and generic sensor array analyser systems that utilize different AW sensor configurations. Initial instruments have implemented arrays of quartz-crystal-microbalance- (QCM-) and SH SAW-based sensors. However, recent developments have led to the implementation of a truly generic system that allows for a greater variety of acoustic and non-acoustic- (conductometric-, capacitive-, . . .) based sensor arrays for operation in either gas or liquid media [38]. The portable and modular microcontrolled system is based on a new parallel system architecture that performs concurrent sampling of the sensor array. Existing systems that have been proposed for either gas or liquid media have generally been on a polling architecture, whereby the acoustic sensors were sampled sequentially [39, 40].

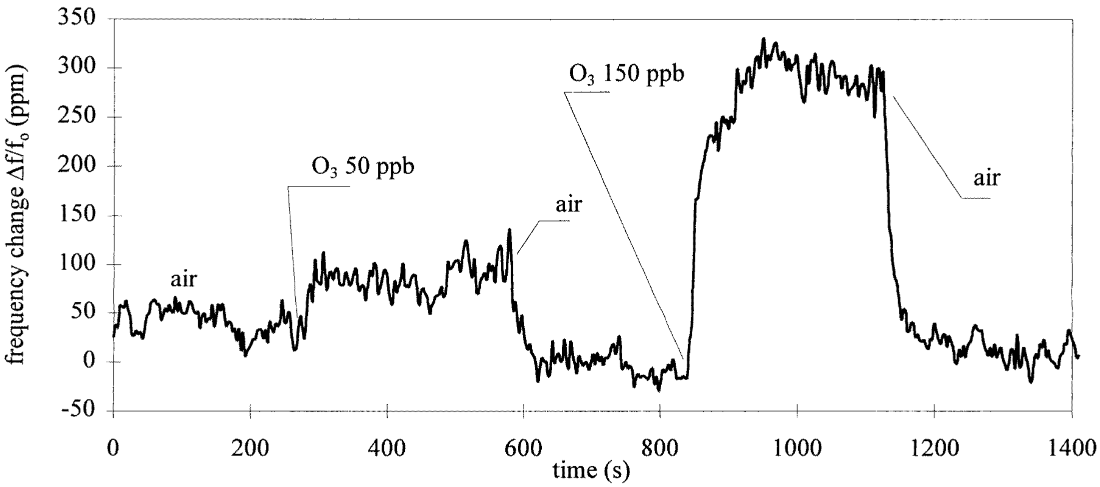


Figure 8. The response of an $LiNbO_3$ SAW ozone sensor to various concentrations (flow rate 1.8 l min^{-1}, 200 °C).

Polling has the disadvantage of data loss especially for a large sensor array when rapid chemical kinetics are involved. Given these conditions only equilibrium state measurements can be made using this technique. The parallel architecture, on the other hand, offers a true parallel sensing environment, allowing for the investigation of sensing interaction kinetics across the entire sensor array.

Figure 10 shows the block diagram for the AW array system depicting the parallel system architecture and figure 11 shows a photograph of the instrument that was used for the SH SAW immunosensing investigations [19]. The system performs the automated control of the liquid/gas delivery and the sensor data acquisition systems. Experimental parameters such as the liquid/gas flow rate, reference and sample flow times and data sampling rates are controlled by the user at the console of the instrument. Experimental data is stored on an IBM PC via a RS232 serial link using a computer program (Microsoft™ Visual C++) which also serves as the user interface for the entire system.

The portable instrument has four functional modes (*purge, cycle, zero* and *calibrate*) that have been designed to allow for greater operational simplicity and can be invoked at any stage during an experiment. Referring to the SH SAW immunosensing investigation as an example, the first two modes refer to the control of the liquid delivery system whereas the second two refer to the calibration of the sensor array data. The *purge* mode continuously pumps a buffer solution through the array, establishing a sensor baseline reference. The *cycle* mode provides a complete, fully automatic analysis facility that switches between the sample and reference liquids. User-specified sensor data sampling and liquid analysis times (reference and sample durations) are pre-selected. The *zero* mode is used for obtaining a stable frequency baseline of the sensors and the *calibration mode* is used to switch between the calibrated reference data and the received raw data of the sensor array.

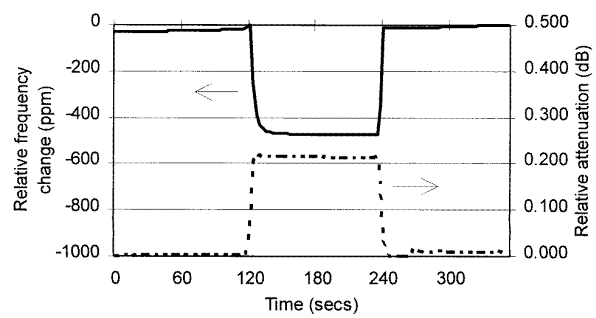


Figure 9. The SH SAW sensor response to Evian™ water sample (flow rate 10 ml min^{-1}, temperature 25 ± 0.1 °C).

5. Future development and discussion

The present authors are of the opinion that the future research direction will be towards the development of smart sensors that integrate different sensor configurations, electronics and MEMS. The focus will be to realize total physical and chemical analysis systems in the one IC package. Such systems would be capable of simultaneously sensing multiple parameters, hence providing a better understanding of the sensing environment.

We have already seen the benefits of the Si integration of acoustic sensors and the electronics [7, 20] and the use of an array of sensors for multiple-parameter sensing [12, 19, 38–40]. These two areas highlight the need to investigate new systems that are more intelligent in the way they sense and interpret their environment. Smart sensors are identified as the next stage in the development. Using a combination of IC compatible technologies, such as Si micromachining, thin-film deposition, chemical layer fixation and integrated electronics, smart structures and systems can be realized. A combination of different sensors, not just those based on acoustic devices, may be integrated into the system. MEMS devices such as pumps, channels for liquid or air, actuators or positioners, for example, would provide further possibilities to investigate new sensing techniques.

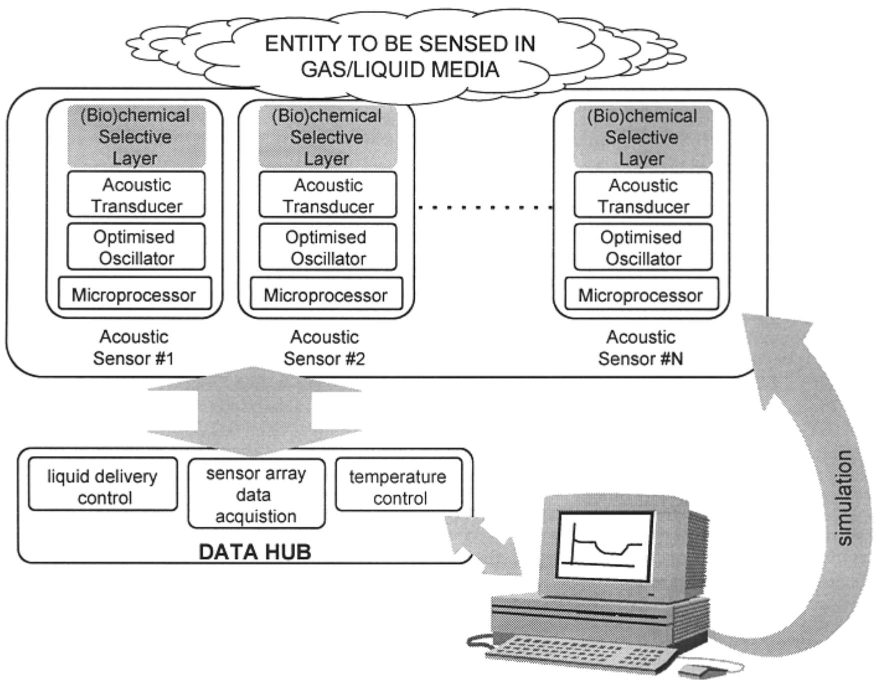


Figure 10. A block diagram of the AW sensor array system.

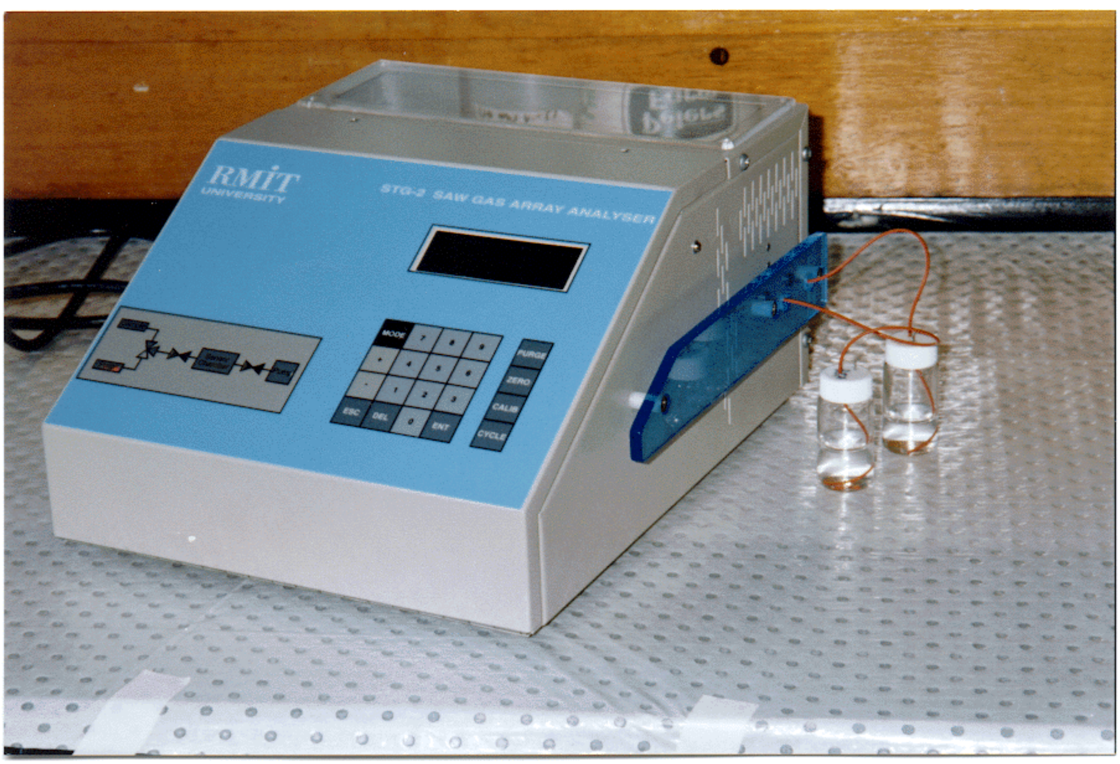


Figure 11. A photograph of the AW sensor array portable instrument.

The particular applications for which the development of total physical and chemical analysis systems are seen as being vital are those systems aimed at environmental monitoring, such as multi-spot continuous monitoring in remote sites and urban areas, and for biosensors. Miniature and fully self-contained smart sensors that are mass fabricated show enormous potential for these applications. The justification for further research towards the integration of the different processes and technologies required is thus clearly apparent.

6. Conclusion

Acoustic wave sensors have shown interesting possibilities in terms of their sensitivity to a number of different parameters in both gas and liquid environments. Many applications of AW devices in the sensors field have been demonstrated. Investigation of a portable sensor array system combined with pattern recognition techniques has demonstrated the feasibility of a liquid analyser. Combining IC-based processes and AW sensor potentialities will allow for the integration of sensor arrays, electronics and MEMS driving actuators for the development of total physical and chemical analysis systems.

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